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INVESTIGATION OF DEUTERIUM IN THE SUN

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-USSR-

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1. State of the Problem

Menzel (1) was the first to discuss the presence of the heavy isotope of hydrogen, deuterium, in the sun. He guessed that the very weak unidentified line in the solar spectrum at λ 4960.024 with an intensity of -3 is the Dβ line of deuterium. Assuming, according to the calibration of the Rowland scale by Russell, Adams, and Moore, that the Hβ line (intensity 30) corresponds to 600,000 times more atoms than a line with intensity -3, he estimated the deuterium concentration to be 1/600,000 of that of ordinary hydrogen. However, this estimate is not reliable, since this calibration of the Rowland scale is not applicable to the hydrogen lines, whose intensity is affected by the Stark effect. Further, examining the Hγ line in the spectrum of a flare (intensity 85), he showed that the weak chromium line with intensity 0 near the Hγ line is definitely detected, while the Dγ line is not found. Hence, using an extremely inaccurate scale of spectral line intensities in a flare, Menzel concluded that the abundance of deuterium is less than 10^{-5}. This conclusion cannot be considered reliable either, since the Dγ line is strongly blended with other lines of much greater intensity (see section 3).

After that time, the problem of deuterium in the sun was not pursued. Only in recent years, when it became clear that the proton-proton nuclear reaction could be extremely effective even for stars of the type of the sun, did the question of the presence of deuterium (which is consumed in such a reaction) receive attention as a peculiar spectroscopic criterion for the existence of such an energy-releasing mechanism. In addition, there was the somewhat unexpected spectroscopic detection of lithium by Greenstein and Richardson (2) and beryllium by Greenstein and Tandberg-Hansen (3), which could not be explained from the theory of the maintenance of the sun's energy by nuclear reactions in the presence of complete mixing of the material inside the sun (from the center to the atmosphere). These authors hence concluded that the mixing is incomplete and only takes place in the exterior part of a star, where the elements could not "burn up" completely because of the comparatively low temperatures.

The idea of the possible presence of deuterium lines in stellar spectra was first proposed in 1951 by G. A. Shayn and, somewhat later, by O. A. Mel'nikov (4).

In 1951, Class (5) attempted to find the upper limit for the deuterium content of the sun, proceeding from the assumption that the Dα line is not observed; in particular it is not found in the Utrecht atlas of the solar spectrum. Assuming that the equivalent width of this line is less than 2 mÅ, he found by the method of weighted functions (which are applied to weak lines) a figure of $4\ 10^{-9}$ as the upper limit of the deuterium concentration, i.e. $5\ 10^{4}$ times less than the concentration on the earth ($2\ 10^{-4}$). However, this attempt to estimate the deuterium concentration is not reliable for the following reasons. First, Class disregarded the fact that the Dα line is almost completely blended with the weak line of water vapor at 6561.105Å (see section 3). Second, as De Jager (6) noted, the blending of the Dα line with the Hα line renders the contour of the Dα line almost imperceptible. De Jager, on the basis of the method he has developed for studying the hydrogen lines, calculated the contour of the Hα line with consideration of the blending from the D line. In addition, he calculated the contour of the Hα line without the Dα line (deuterium concentration was taken as $2\ 10^{-4}$). These calculations showed that in that part of the Hα contour where the Dα line should be located a small depression (about 2% at the exact center of the Dα line) should be observed in the Hα contour. Comparing this theoretical result with the data in the Minnaert atlas, De Jager noted that at a distance of 0.2Å on the blue side of the center of the Dα line (near 6560.8Å there is indeed a sort of depression, since the undisturbed wing of the Hα line should be 0.7% higher than is shown in the atlas. This gave him reason to conclude that deuterium possibly exists in the solar atmosphere in a concentration comparable with that in the earth's atmosphere (he considers that $1\ 10^{-4}$ is the most probable figure).

The same author rightly notes that if an unblended Dα line (for a concentration of 10^{-4}) were comparatively strong, with a depth of 12%, a half-width of 0.7Å, and an equivalent width of 92 mÅ, then the Dα line blended with the Hα line would have a total depth of 2% and an equivalent width of 7 mÅ, 13 times less than the unblended line. De Jager also noted that the deuterium lines cannot be treated like weak lines, since they are caused by strong absorption in deep layers (the upper layers practically do not participate in selective absorption), and, therefore, Class' method of weighted functions is inapplicable. The Dα line is as if veiled by the continuous radiation of the outer layers.

However, De Jager disregarded the fact that the 6560.8Å region, where the Minnaert atlas indicates a slight depression, may be related simply to the effect of blending from the neighboring line at 6560.570Å, which consists of a water vapor line and an unknown diffuse solar line (see section 3). In addition there is also a very weak telluric line in this region at low altitudes of the sun (see below).

Gauzit (7), proceeding from more accurate wavelengths for deuterium, recently attempted to measure the intensity of the $D\beta$ line in the Minnaert atlas and the intensity of the line D (3-5) at $\lambda 12814.56$ Å of the Paschen infrared line in the Michigan atlas of the infrared solar spectrum (Ref. 8). He found that the assumed $D\beta$ line at $\lambda 4860.24$ Å has an equivalent width of 1.5 m Å. The wavelength of the D (3-5) line is very close to that of an as-yet-unidentified line at $\lambda 12814.64$ Å with an intensity of -2. For this line Gauzit finds an equivalent width of about 10 m Å. A similar study was conducted by Crespin (9), who used the Minnaert atlas and infrared solar spectra obtained by De Jager and Neven. Crespin found that the $D\beta$ and D (3-5) depressions in question, if they do exist, are of the same order of magnitude as the unevenness of the background caused by the inaccuracy of the photographic method. In spite of this, the author determined the equivalent width of $D\beta$ as 4.1 m Å (with an error of a factor of two or more) and the equivalent width of d (3-5) as 2.7 m Å.

Gauzit and Crespin, on the basis of these measurements, estimate the deuterium concentration as about 10^{-4} which agrees with De Jager's estimate. This agreement is, however, quite accidental, since these authors did not consider the blending effect from the hydrogen lines. In addition, their evaluation of the intensity of the $D\beta$ line, just as the original estimate by Menzel, is extremely unreliable, since the $D\beta$ line, if it does exist, is very strongly blended with the iron line at $\lambda 4859.749$ Å.

De Jager (10) has accounted for the blending in a re-examination of the problem of the depressions of the D (3-5) and D (4-7) infrared lines and found that even for a deuterium concentration of $7 \cdot 10^{-4}$ the depression of the D (3-5) line, presumably identified with the line observed at 12814.56 Å, would be less than 0.1%. But for such a deuterium concentration, the $D\alpha$ line would be strong enough to be observed easily. Therefore, the identification of the line at 12814.56 Å with the D (3-5) line is incorrect. The same is valid for the D (4-7) line, which was identified with the line at λ 21648.37 in the Michigan atlas (8). In the same article (10), De Jager listed a depression in the $D\alpha$ region which he determined from the Minnaert atlas, and, by comparing it with the theoretical contour of such a depression computed with an account of the blending of $D\alpha$ and $H\alpha$, finds a deuterium concentration of $1.45\ 10^{-4}$. However, the criticism made above relative to the earlier work of this author (6) is also applicable here.

The present author has made photoelectric studies of the $H\alpha$ and $H\alpha$ lines in flares and in undisturbed portions of the solar disk, and in the beginning of 1954 (Ref. 11) detected a constant phenomenon of weak assymmetry of the contours of these lines for the undisturbed portion of the disk. A similar phenomenon could not be established with certainty for the flares, since in flares there is a very peculiar distribution of emission and absorption in the wings. This assymmetry was detected as a depression of the blue wings of these lines, which is greatest in the region of the $D\alpha$ and $D\beta$ lines. This depression was ascribed entirely to the $D\alpha$ and

D_β lines, and according to its equivalent width, a deuterium concentration several times greater than that for the earth was deduced.

2. Results of Our Preliminary Measurements

The wide (total width about 5 Å) depression that we detected (11) near the D_α line with a depth of about 3% cannot be entirely ascribed to the deuterium line [See Note] Actually, the absorption line of deuterium, if it has not yet been detected, should be a weak line with an intensity not greater than -2, -3 on the Rowland scale (no stronger than the weakest lines of this catalog). (Note: The author is indebted to I.S. Shklovskiy for critical comments on the question of the nature of the depression observed in Ref. (11) (see Ref. 24).

For weak lines the width is practically independent of the number of absorbing atoms and is a result of the Doppler effect. The half-width of the Doppler contour for the D_α line will be $\sqrt{m_D/m_H} = \sqrt{2}$ times less than the half-width for the H_α line, which is 0.212 Å at a temperature of 5470°. The fact that the D_α line is located in the wing of the H_α line can lead to blending and to some amplification of the linear absorption of the H_α line in the D_α region (the absorption coefficients for H_α and D_α are added). In the region of the D_α line the residual intensity in the H_α line is $r_\nu = 0.82$, and for a rough estimate one can use the arguements which are valid for an optically thin layer, when the depth of the line is $R_\nu \approx \tau_\nu$, where τ_ν is the optical thickness. Since deuterium atoms differ from hydrogen atoms only in mass, the ratio of the depth of an H_α line in the D_α region (at a distance $\Delta\lambda$ of about 1.8 Å) in the absence of D_α to the depth of an H_α line that is blended with D_α will be approximately

$$\frac{R_\nu(H_\alpha + D_\alpha)}{R_\nu(H_\alpha)} \approx 1 + \frac{D}{H}\frac{s_\nu(D_\alpha)}{s_\nu(H_\alpha)}, \tag{2.1}$$

where D/H is the ratio of deuterium and hydrogen concentrations, and s_ν is the atomic absorption coefficient. The ratio

$$\frac{s_\nu(D_\alpha)}{s_\nu(H_\alpha)} = \sqrt{2}\,\frac{\varphi(v')}{\varphi(v)}, \tag{2.2}$$

where $v' \approx \Delta\lambda/\Delta\lambda_D(D_\alpha)$, $\Delta\lambda$ is the distance from the center of D_α, and $\Delta\lambda_D(D_\alpha) = \Delta\lambda_D(H_\alpha)/\sqrt{2} = 0.150$ Å; $v = \Delta\lambda/\Delta\lambda_D(H_\alpha)$, $\Delta\lambda$ is the distance from the center of H_α, ($\Delta\lambda_D(H_\alpha) = 0.212$ Å), and

$$\frac{s_\nu}{s_0} = \varphi(v) = e^{-v^2} - \frac{a}{\sqrt{\pi}}(1 - 2vF(v)),\quad a = \frac{\gamma}{\Delta\omega_D}; \tag{2.3}$$

the magnitude of $\underline{a}$ for the D_α line is $\sqrt{2}$ times greater than it is for the H_α line. It is not difficult to compute $\varphi(\nu)$ and $\varphi(\nu')$ for the center of the D_α line ($\Delta\lambda = 1.79$, $\nu' = 0$) with the aid of a table of the functions $1 - 2vF(v)$ (see Ref. 12). Considering that the wings of the H_α line are determined by collisions (Ref. 13), we find that $\varphi(\nu) = 1.652 \cdot 10^{-3}$ and $\varphi(\nu') = 0.8115$, whence the ratio (2.2) will be ~ 690; consequently, for the ratio (2.1) we obtain $1 + 690(D/H)$, whence we find that D/H is not greater than $5 \cdot 10^{-5}$ for a depth of the depression of about 3%. The width of the depression is determined approximately (neglecting the change of $\varphi(\nu)$ on the sector of the D_α line) by the magnitude of $\Delta\nu'$, which corresponds to a decrease of $\varphi(\nu')$ by a factor of two in comparison with $\varphi(0)$. In any case, $\Delta\nu'$ is less than one. Even if we take $\Delta\nu' = 1$, we obtain $\Delta\lambda' = 0.212/\sqrt{\lambda} = 0.15$ Å, so that the D_α line must be very narrow with a total half-width no greater than 0.3 Å. This discussion, however, corresponds to the case of an optically thin layer and does not account for the difference in the depth of formation of the various parts of the H_α contour, the change in the absorption coefficients with depth, or the model of the solar atmosphere.

De Jager (10) recently calculated the H_α contour as blended with the D_α line with account of these factors. His calculations give a depression width of about 0.6 Å for a central depth of about 1%, which corresponds to a concentration $D/H = 1.4\ 10^{-4}$ and a width ~ 0.5 Å for a central depth of 0.5% ($D/H \approx 7\ 10^{-5}$). Henceforth, we shall use these calculations for comparison with observations. Now we must only mention that according to these calculations the contour of the depression caused by the D_α line is slightly assymmetric: the depression extends further into the blue portion than into the red. The fact that blending causes such an assymmetry is evident from formula (2.2): the function $\varphi(\nu')$ gives a symmetric distribution near $\lambda(D_\alpha)$, ($\nu' = 0$), while the function $\varphi(\nu)$ declines continuously in the violet over the entire portion of the spectrum in which the D_α line can appear. Therefore, the depression in the H_α line caused by the D_α line should be greater on the violet side of the center of D_α than it is on the red side. Account of the change in $\varphi(\nu)$ is also basically responsible for the increased width of the depression in comparison with the usual calculation (an effect similar to the drop in the level of the continuous spectrum in the vicinity of the line). In measuring the position of a weak D_α line this could lead to a slight fictitious shift of the line to the violet, an effect that we shall discuss below.

Thus, the depression that we have detected (Ref. 11) is also related to the D_α line, but only in part. In the vicinity of the possible D_α line there are also the lines*listed in Table 1.

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*According to the Rowland atlas.

TABLE 1

λ	Δλ	Element	Intensity	
			Disk	Spot
6557.865	0.297	Atm	-8	-
58.162	0.438	wv	-1 N	-
58.600	0.363	Atm	-3 N	-
58.963	0.625	Atm	-3	-
59.588	0.233	Ti +	0	-1
59.821	0.262	?	-3	-
60.083	0.183	?	-3	-
60.266	0.304	?	-3	-
61.105	1.711	wv	-2	-
60.570	0.535	wv	-1 Nd?	-0
62.816	-	H_α	40	20

We see that the separation between successive lines is almost everywhere less than 0.5 Å. The isotopic structure of the H_α line shows a shift of D_α relative to H_α which equals 4.14 cm^{-1} or 1.79 Å (Ref. 14) so that

$$\lambda (D_\alpha) = 6561.026 \text{ Å},$$

and the D_α line (if it is present) should be located between the water vapor lines at 6560.570 and 6561.105 Å (very close to the latter). Since as a result of blending with the H_α line the half-width of the D_α line can still be great (0.5 Å), it will not appear as a separate line between the two water vapor lines, which are separated by 0.535 Å, but will be a blend and may be manifested as a depression between the water vapor lines even with an instrument of very high resolving power. A low-resolution instrument will record an overall depression caused by all three lines, and possibly by other neighboring lines to the blue side, which have an intensity of -3 (6560.266, 6560.083, 6559.821), i.e. a depression extending more than 1 Å.

To clarify the nature of the depression detected by us (Ref. 11), in the summer of 1954 we made new recordings with the earlier instrument and examined the results of the individual recordings. The fact is that the global representation of all measurements in Ref. (11) could have lead to distortions: in averaging individual results an incorrect representation (because of inaccuracies in individual recordings) related to the method of division into groups may have arisen. In Fig. 1 we show the results of processing of individual series of recordings of the H_α line: along the y-axis are plotted differences in the residual intensities of the red and blue wings of the H_α line in the sense of red minus blue (as percentages of the continuous spectrum), and along the x-axis is plotted distance from

the center of H_α in angstroms. Each series, obtained in the course of one day, contains up to 5 individual recordings. In distinction to the recordings of 1953 (Ref. 11), these recordings were made at the slowest possible scanning speed (about 1/15 cps), in order to avoid distortions due to the presence of a time constant in the recording oscillograph.

Almost everywhere in Fig. 1 we can see 2 humps by the depression: one is in the region of the D_α and water vapor lines, while the other is almost certainly related to the TI^4 line at 6559.588 Å. The magnitude of the first hump varies from case to case, which is probably related to the varying strength of the water vapor lines, which depends on the altitude of the sun and, of course, on the amount of water vapor in the atmosphere. In addition, the two humps are blended together, which is due to the low resolving power of the equipment used to make the recordings in 1953-54. The actual resolving power of the photoelectric recordings has been studied by E. Ye. Dubov (see his article in this volume). The resolving power of a recording is determined by the input time constant of the oscillograph amplifier, the unevenness of the rocking rate of the mirror, the finite width of the electrophotometer slit, and, of course, by the resolving power of the spectrograph itself. The spectrograph grating used was 110 mm in size and had 600 lines per mm. Recording was done in the first order, and the theoretical resolving power was therefore 66,000 or about 0.1 Å. The instrument contour from the spectrograph was close to this value (0.16 Å). For certain resolution of a D_α line (6561.026 Å) near the atmospheric line at 6561.105 Å, the resolution of the recording should be not less than 0.08 Å. Therefore, even with an infinitely high resolution of the photometer, the D_α line, because of its width ($\sim$ 0.5 Å) should be strongly blended with the line at 6561.105 Å.

In our recordings of 1954 we used a spectrograph inlet slit equal to 3-4 normal for the purpose of increasing spectrum brightness and also decreasing the noise of the FEU [Fotoelektricheskiy Usilitel' -- Photoelectric Amplifier], and a photometer slit of about 0.36 Å, i.e. more than twice as great as the instrument contour. The actual spectral resolving power was about 0.25 Å on the average, which is about one and one-half times less than the width of the photometer slit. As recorded by the photometer, the contour of an infinitely narrow line, because of the smoothing effect across the slit (0.36 Å) was (the calculation is given in Ref. (15)) approximately one and one-half times as wide as the actual contour (0.25 Å), i.e. was approximately 0.4 Å. Therefore, the D_α line in our recordings could also have been blended with the second water vapor line at 6560.570 Å.

Further, the effect of assymmetry of the H_α line can be caused by distortion of the form of the contour because of the presence of the RC circuit -- a time constant at the amplifier input. This distortion is proportional to the steepness of the contour; it is determined by the ratio of the time of passage of a portion of the width of the instrument contour past the photometer slit (scattering circle) to the time constant. The slower

this portion passes (for a given RC) across the slit, the less this distortion will be. For our recordings the ratio of these times is determined as follows. The width of the entire recorded portion of the spectrum is about 80 Å, the recording time is 15 sec; therefore, the time of passage of the actual instrument contour (0.25 Å) across the slit is $t \approx 1/20$ sec. The assumed τ = RC was approximately 10^{-3} sec, and consequently $t/\tau \approx 50$. Portions of the spectrum containing lines wider than 0.4 Å, including the H_α line, were recorded without distortion (the calculations are given in Ref. (15)), which was confirmed by a comparison of recordings made with forward and reverse scanning. Consequently, distortions could have arisen mainly as a result of the smoothing effect of the photometer slit and widening of the spectrograph slit. Unevenness of the movement of the spectrum could not have distorted the recordings with the system used to synchronize the scanning.

In summing up, we can say that the method of spectrum recording used in 1953-1954 gave a resolving power of about 0.4 Å, which caused unavoidable blending of individual lines and led to the appearance of a depression from the blending of three lines: water vapor lines at 6561.105 and 6560.570 Å, and, partly, the Ti^+ line at 6559.588 Å. The depression shown in Fig. 1 cannot, of course, be entirely identified with D_α. However, the sector from the center of H_α to D_α (to the red side of D_α.) contains only one weak line of water vapor at 6561.105 Å, i.e. this sector is relatively unblended. We see that all the recordings (see lower part of Fig. 1) show a depression in this sector and its characteristic growth toward λ (D_α), which can hardly be ascribed entirely to the effect of the water vapor line, which is separated by about 1.7 Å from the center of H_α. Fig. 2 shows the average contour of this depression corrected for the instrument contour and constructed by means of averaging the left-hand wing of the depression (in the sector from the center of H_α to D_α) for the separate series. In the same figure we also show the red wing of the D_α depression (shown by small open dots), as calculated by De Jager (6) for a concentration $D/H \approx 2 \cdot 10^{-4}$. We see that the observed depression is nevertheless considerably larger than the possible depression related to the presence of deuterium. It is difficult to assume a greater deuterium concentration, since we would then observe it easily in the chromosphere. The question of the possibility of observing deuterium in the chromosphere will be discussed below. Therefore, to settle the question of deuterium lines in the solar spectrum, it became necessary to have recordings with a considerably greater resolving power.

3. New Measurements with High Resolving Power

These measurements were carried out in 1955 on the spectrograph of the new BST [Bashennyy Solnechnyy Teleskop -- Tower Solar Telescope] (for a description, see Ref. (16)). The principle circuit of photoelectric recording remained the same as in Ref. (11), but for the new spectrograph a number of changes and improvements were introduced to increase the accuracy of recordings:

1. A large new rocking mirror, whose dimensions exclude the possibility of vignetting of the edges of the portion of the spectrum to be recorded.

2. By changing the eccentrics which oscillate the yoke of this mirror, it is possible to record portions of the spectrum of varying length (8 and 60 Å).

3. Installation of a specially designed reduction gear makes it possible to record with a wide range of speeds (from 4 to 1/500 cps) depending on the program of recording. Weak lines should be recorded at a low speed, strong lines at a greater speed; in each case the speed which does not cause distortions, for a given RC, can be selected either by means of calculation or by comparison of recordings made in forward and reverse directions.

4. It has been made possible to select and quickly change the RC at the oscillograph amplifier input, which permits reduction of distortion from the noise of the FEU to any desired magnitude (say 0.5% and less) and change of recording sensitivity.

5. Two easily interchanged FEU are used: antimonycesium for the visible portion, and bismuth-cesium for the /infra-/ red portion; we used FEU VEI /Vsesoyuznyy Elektro-tekhnicheskiy Institut imeni Lenina -- All-Union Electrotechnical Institute imeni Lenin/ with low noise-signal ratio and small dark current.

6. An improved spectrum sweep circuit in the oscillograph cathode. Fig. 3 shows the optical system of the new installation /See Note/. An image of the sun, 220 or 350 mm in diameter, is projected on the inlet slit S_1 of the BST spectrograph. The beam from the collimating mirror m_1 (230 mm in diameter) falls on the grating G, which is 150 X 140 mm, is ruled at 600 lines/mm, and has maximum light concentration in the second order (this was just replaced by a grating of higher resolving power; see below). The spectrum from grating G falls on the camera mirror m_2 (300 mm in diameter), which projects its image, 180 mm long, on the adapter A under ordinary circumstances. By introducing the diagonal mirror m (180 mm long and 60 mm high) into the beam m_2A, the spectrum image can be projected onto the plane of the electrophotometer slit S_2 (the mirror m is moved forward and backward in the direction mS_2 along guides). The photometer lens l_4 projects the image S_2 onto the cathode of the photomultiplier P_2 (one can change from the FEU P_2 to the other FEU P_1 by moving the box in which they are located). The varying photocurrent, which arises in the oscillation of mirror m and the displacement of the spectrum relative to the slit S_2, is fed through the amplifier U_V to the vertical plates of the cathode oscillograph R. Horizontal sweep of the spectrum is also photo-electric, by means of periodic modulations of an auxiliary light beam in the following manner. (Note: Original design of the electrophotometer device was carried out in 1951 by V. V. Nikonov and the author (17)).

The strongly diverging beams from the lamp L, passing through lens l_1, fall on the slit S_3, creating an even illumination upon it; lens l_2 projects the image of this slit upon the triangular diaphram t by means of reflection of the beam from the same mirror m. Behind the diaphram t is a Fabry lens l_3, which projects onto the cathode of the FEU P_3 the sector of mirror m which does not move during the oscillation (the sector which passes through the axis of rotation, which lies in the plane of the mirror). Thus, at the FEU P_3 there is an unmoving light spot whose brightness changes according to a saw-tooth curve. The output of the FEU P_3 is fed to the horizontal plates of the oscillograph F via the amplifier V_h. Such a system assures a completely reliable synchronization between the displacement of the spectrum along the slit and its horizontal sweep. In synchronization with the oscillations of mirror m, the shutter at the spectrograph slit S_1 closes once per half-period of the mirror's oscillation, which allows recording of the spectrum during the first half of the oscillation period and of the dark line (the dark current of the FEU) during the second half. The scale of recordings depends on the amplifications at U_v and U_h, and, of course, on the magnitude of the light beam and the sensitivity, which is determined by the resistance at the amplifier inputs. Traces on the oscillograph screen and photographed on standard 35-mm motion picture film with a motion picture camera placed in front of the screen. Since the screen of the cathode ray tube is not completely flat, there is a slight distortion at the edges of the field; this is corrected by a specially designed transparent overlay grid.

This effect must be considered only in constructing the contours of wide lines which are traced on the entire screen. For recording weak, narrow lines we used a recording amplitude of 6 to 8 Å and a speed of less than 1/100 cps with large time constants (up to 0.1 sec). The use of large RC is helpful for weak lines since fluctuations of the photocurrent, which can be comparable in magnitude with the depth of the line to be recorded. An amplitude of 60 Å and a speed of about 1/10 cps with a minimal time constant can be used to record wide lines. Figure 4 is a photograph of the photoelectric attachment to the BST just described.

Recording on the photoelectric attachment was made with the spectrograph slit equal to the normal λ (f/d) = 0.03 mm. The instrumental contour of the spectrograph was 0.04 Å (0.025 Å for the new grating) according to our measurements, which is 0.01 Å greater than the theoretical half-width of the contour of an infinitely fine line (the theoretical resolving power was 180,000 and later 300,000). With a 0.7 Å /mm dispersion in the second order (later 0.3 Å /mm) the width of the instrument contour was 0.06 mm. The width of the photomenter slit S_2 was set at 0.05 mm, somewhat less than the half-width of the instrument contour. Under such conditions, the smoothing effect of the photometer slit on the line contours can be disregarded, and one can assume that the resolving power of recording is practically the same as the resolving power of the spectrograph (in any case, not more than 10% less than the latter). The recording of an 8 Å sector was made

at a speed of about 1/100 cps so that the time t of passage of a sector with a width of the instrument contour of 0.04 Å was 0.5 sec. With a minimal time constant of $\tau \leq 0.01$ sec, the ratio $t/\tau \approx 50$, i.e. all lines wider than 0.05 Å were recorded without distortion; there were practically no fluctuations in photocurrent in the recordings. This is also evident from a comparison of individual recordings: they coincide with each other within less than 1%. To eliminate any possible effects from unevenness in the oscillations of the mirror, we always made two series of recordings, one in each direction. As a rule, these recordings coincided within a fraction of 1%.

Figure 5 is an example of a single recording of the blue wing of the H_α line from the center of the disk and the western limb. From this picture it is evident that our recording reproduces with complete reliability all the weak lines of the Rowland atlas with intensity not less than -2 (for example, the line at 6563.533 Å, and others). The weakest lines with intensity -3 are recorded clearly, although with less certainty (for example 6559.821, 6560.266, etc.). We have not found a single line in the Minnaert atlas which would not have been recorded by our equipment; on the contrary we detected a number of lines that are not given in either the Rowland catalog or the Minnaert atlas (for example, 6561.68 Å). At the limb, for example, there is a very clear splitting of the blend at 6560.570 Å, which is ascribed doubtfully (Nd) in the Rowland atlas to the water vapor line. There is no doubt that there is an unidentified solar line in this blend (see below).

The high accuracy of our method allowed us to set the following task: is there a change from the center to the limb in the magnitude of the depression between the water vapor lines at 6560.570 and 6561.105 Å? If between these telluric lines there is a weak and sufficiently wide line of solar origin (more accurately, a wing of a line), the magnitude of the depression related to it should change from the center to the limb, while the shape and equivalent width of the telluric lines should remain constant. But the shape and width of the lines at 6560.570 and 6561.105 Å may be not strictly constant, since a possible D_α line would be blended with these water vapor lines. Let us examine this question in more detail.

The line at 6560.570 Å is a very close blend of a water vapor line and a solar line of unknown origin; its equivalent width will change noticeably from the center to the limb. On the other hand, the D_α line (6561.026 Å), as is evident from Table 1, is very close to the water vapor line at 6561.105 Å.

However, this wavelength for the D_α line was obtained by subtracting from the wavelength of the H_α line, 6562.816 Å, the isotopic displacement $\Delta\lambda = 1.79$ Å without consideration of the components of the fine structure of the H_α line. In the spark spectrum the H_α line is a close doublet (Ref. 18) whose wavelengths are 6562.849 and 6562.725 Å (with

intensities of 2000 and 1000, respectively). Thus, the separation of the components of such a structure, 0.124 Å, is three times greater than that of a structure which is at the limit of resolution of our spectrograph. If the fine structure does not affect the contour of the H_α line because of its great width (broadening it slightly and making it perhaps assymmetric), then the width of the weak D_α line will be in all several times greater than the doublet separation. This situation is ordinarily not examined in astrophysics and for some reason was ignored in the examination of the question of deuterium on the sun. Thus, the D_α line should be a very close blend of two lines at 6560.964 and 6561.088 Å. The second component is actually almost completely blended with the water vapor line at 6561.105 Å (it is 0.02 Å toward the blue side of the center); the first component is close to the center of the interval between these two water vapor lines. Therefore, if there is a depression between these water vapor lines that is related to D_α, then the main contribution to it is given by the component at 6560.964 Å since the component at 6561.088 is almost completely blended with the line at 6561.105 Å. This could lead to a situation where the 6561.105 line could also change in equivalent width from the center to the limb. However, this effect would be strongly dependent on the intensity of this line, i.e. on the concentration of water vapor in the earth's atmosphere and on the altitude of the sun.

In 1955, we made 90 recordings for the center and limbs of the sun. The recordings of the limb and center at different altitudes of the sun were made practically at the same time according to a scheme: limb -- center, or eastern limb -- center -- western limb, etc. They were divided into groups (an average of 5 recordings per group) taken at approximately equal altitudes of the sun; after conversion into residual intensities, the average contour for each group (for the center and the limb) was derived. Here the most delicate question is the drawing of the "continuous background", i.e. the wing of the H_α line in the region in question. The contour of this region, which contains the 6561.105 and 6560.570 lines, was constructed in units of the variable residual intensity of the wing of the H_α line. But since the sector occupied by this region is small, this drawing becomes sufficiently reliable (see Figure 5). We based our construction of the wing of the H_α line in this region on the points a, b, and c. Inasmuch as the H_α wing is not a straight line between a and c, the point b is always lower than the H_α wing, i.e. there is a depression between 6561.105 and 6560.570 Å, especially at the limb. It is also observed in the majority of cases in which a and c are connected by a straight line, which is incorrect. In place of such a straight line, we tried to draw a smooth curve as close to this straight line as the shape of the wing to the left of a and to the right of c would allow. Some of these drawings were done by two people for a check.

The results of treating two of the most reliable recordings made with a resolving power of 180,000 (made on 7 and 10 June and 11 October 1955) are shown in Figures 6 and 7. These results are characteristic in

that they were obtained for varying water vapor concentrations: high concentration (19:00, 7 June; 18:00 10 June), moderate (7:15 - 15:00, 7 June), and low (11:30, 11 October). In Figures 6 and 7, the scale d indicates the resolving power of the recordings. From the recordings in Figure 6 that were made when water vapor concentrations were high and moderate, it follows that at the (western) limb the line at 6560.570 Å is almost separated into two lines, of which the blue component rather noticeably changes in intensity, while the red component does not vary and has a residual intensity of about 0.85 (in units of the corresponding r_ν of the H_α wing). At the center the two components are as if merged. Because of the sun's rotation, there is a shift of 0.044 Å in a solar line from a region on the limb of the sun at the equator. If we consider that for the western limb a solar line is shifted to the red and that the red component remains practically constant in intensity, we conclude that this component is a solar line, while the blue component is a water vapor line. That this component is a solar line is confirmed by its amplification in a spot. The resolving power of the recordings does not allow us to determine the shift of this component precisely; it is approximately 0.11 Å. It may in fact be less because of the increase in the equivalent width of this solar line toward the limb. Thus, the shift of the solar line with respect to the water vapor line, reduced to the center of the disk, will be approximately +0.055 Å. Since the wavelength 6560.570 Å is attributed to the center of the blend, then the probable wavelength of the solar line of unknown origin is 6560.62 $\pm$ 0.02 Å.

The nearest (in wavelength) line to this one, which could be observed with difficulty (because of low inoization potential), is the SiI line with a wavelength of 6560.68 Å in the laboratory, and 0.03 to 0.05 Å greater than this in the solar spectrum. It would be difficult to attribute a divergence of about 0.10 Å to errors, and this solar line remains unidentified for the present [See Note]. The results of the observations of 11 October (Figure 7) do not show a splitting of the 6560.570 line at the limb, which would seem to contradict what we have just said. However, the recording of 11 October was made especially on a day when there was a strong, hot east wind, which made the air very dry. During the recordings of 11 October, the transparency remained surprisingly stable. This is evident if only from the fact that the intensity of the neighboring water vapor line at 6561.105 Å is very low (its contrast is about 3%, i.e. 4 times less than in the recordings of 7 and 10 June). Therefore, the recording from 11 October shows a blend consisting chiefly of the solar line. This also follows from the noticeable increase of the equivalent width of this blend from the center to the limb. (Note: In addition to the 6560.68 line of SiI, there should be two more lines belonging to the same multiplet in the solar spectrum: 6555.20 and 6527.49 Å (see Moore's table (20)). In the region of the first wavelength there is an unidentified line at 6555.54 Å (rather strong) and a comparatively wide but weak line at 6555.15 Å (which is not listed in the Rowland catalog). In the region of the second line there is a strong, unidentified line at 6527.223 Å, and in its wing there

is still another broad, weak line at 6527.606. In both cases the 6555.20 and 6527.49 lines of SiI are strongly blended, and their presence could be suspected. Although the whole question of the existence of such a weak SiI multiplet (laboratory intensity 2n; excitation potential 1.9 v) deserves more detailed study, it is strange that stronger SiI lines with a similar excitation potential have not been detected in the solar spectrum.

Let us now consider the main problem of the depression between the water vapor lines. The results shown in Figures 6 and 7 show that between the lines at 6561.105 and 6560.570 Å there is a clearly expressed depression whose magnitude increases from the center to the limb of the sun. In Table 2 we show the results of measurement of the equivalent width of this depression.

TABLE 2

Date, Time	S_D (mÅ)		S_D (limb)	S_W (mÅ)		S_W (limb)
	Center	Limb	S_D (center)	Center	Limb	S_W (center)
7-6-55						
7:15	1.2(3)	2.0(9)	1.66	8.1	8.1	1.00
9:30	1.6(3)	2.1(4)	1.31	5.7	6.3	1.10
15:00	1.4(4)	2.1(5)	1.50	4.6	5.4	1.18
19:00	1.8(5)	3.8(5)	2.10	18.9	17.6	0.93
10-6-55						
18:00	2.0(3)	3.7	1.85	17.6	20.0	1.17
11-10-55						
11:30	0.5(5)	1.8(5) W	3.6	1.7 W	2.7	1.58
		1.4(5) O	2.8	- O	2.1	1.23
9-11-55						
12:00	0.76(3)	1.3(4)	1.65	3.6	4.5	1.28
Average	1.30(26)	2.16(39)	1.66	-	-	1.18

The first column shows the date; the second the equivalent width S_D of the depression (in mÅ = 10^{-3}Å) at the center and at the limb, the residual intensity of the H_α wing in the region of the depression being taken as 0.82; the third the ratio between the values of S_D at the limb and in the center; the fourth and fifth the same information for the water vapor line at 6561.105. The recording of 9 November 1955 was made in the third order with a different grating (see below). It is first necessary to evaluate the precision of determining the contour of the depression. For the recording of 11 October when the depression was of the lowest magnitude, we obtained the following values for the mean deviation a from the average contour of the depression and the mean square error e of an individual measurement of the contour of the depression (as percentages of the intensity of the H_α wing in this sector; see Table 3).

TABLE 3

Contour	a	ε	R_D
Center	0.2	0.26	1
Eastern Limb	0.56	0.76	3.2
Western limb	0.34	0.46	2.5

In the fourth column we give the central depth R_D of the depression (in the same units). The ratios R_D/ε show that the contour of the depression is determined on the average with an error which does not exceed $\pm$ 25%. This error, which characterizes the divergence between individual recordings, is approximately the same as in our first measurements (Ref. 11). As concerns the precision of determination of the equivalent width S_D, the error here may be related to some uncertainty in constructing the contour between the 6561.105 and 6560.570 lines, which is not disturbed or blended with the depression, for the limb of the disk (the dotted line in Figures 6 and 7). The fact is that the line at 6560.62 Å is diffuse; at the limb it broadens, and its wing may extend (particularly at the western limb) to the sector in which we are interested. However, even if we try to draw the blue wing of the 6560.570 line allowing an unnatural kink in it near the depression so as to lower the dotted line, the value of S_D for the limb will not be decreased by more than 30%, and the value of S_D (limb)/S_D (center) will not go beyond 1.4. Thus, the fact that the depression between 6561.105 and 6560.570 is approximately one and a half times as great at the limb as at the center of the disk cannot be ascribed to the broadening of the unknown solar line at 6560.62 Å at the limb.

At the same time we noticed on spectrograms as well as on the photoelectric records that at low altitudes of the sun (about 5°) there is a barely noticeable, very weak and narrow telluric line at 6560.8 Å, which however, is not at all noticeable at high altitudes. The possibility that the depression is a blend of this line (although not noticed directly) and the red wing of the 6560.62 line is a delicate question for our study. It is obvious that such a blend could also show a center-limb effect.

To clarify this point, we photographed the spectrum of the H_α region in the fourth order for the center and eastern and western limbs of the sun simultaneously with a new grating for the BST spectrograph with a dispersion of 5 mm/Å (Figure 8). We see that at the western limb the 6560.62 line is clearly shifted to the red side of the telluric line because of rotation and can blend with the sector in the western limb and draw a similar wing on the red side, this wing would not reach point a

(except, it is true, for low altitudes of the sun, where the water vapor line is extremely intensive in this wing). (Note: This, of course, is valid, if only the 6560.62 line is not a component of some molecular band from the sun)

Therefore, this depression and its increase from the center to the limb cannot be ascribed to overlapping of the red wing of the 6560.62 line and the 6560.8 (?) telluric line, which is above the detection threshold only at low altitudes of the sun. On the other hand, if we assume that this depression is related to D_α (mainly with the component at 6560.964 Å), the following facts become understandable:

1. The increase of the depression's equivalent width from the center to the limb, as for any weak line on the solar spectrum;

2. The appearance of a very weak depression at point a only at the limb;

3. A small but very well expressed (for minimal intensity of the water vapor lines) increase toward the limb of the equivalent width of the 6561.105 line, which is blended with the second D_α component at 6560.088 Å (see Figure 7 and columns 5-7 of Table 2 for the records of question /See Note/. However, at the eastern limb it is entirely superposed on the 6560.570 line of water vapor and frees the sector in question from blending even more so than at the center. Therefore, the increase in the depression from the center to the limb (particularly the eastern limb) cannot be related to a blend of the red wing of the 6560.62 line, because of its displacement, and the telluric line 6560.8 (?), which appears at low altitudes of the sun. (Note: Measurements of this spectrogram also give a wavelength of 6560.62 Å for the unknown line.)

If this depression were entirely a telluric line, then one could not understand the appearance only at the limb of a depression at point a (Figures 6 and 7), where the blue wing of the 6561.105 line and the possible red wing of this "telluric" line would overlap. It is obvious that we cannot ascribe the appearance at the limb (particularly the eastern limb) of a depression at point a to the effect of the red wing of the 6560.62 line that is broadened at the limb: for this, at a depth of about 10% ($r_V = 0.90$) the red wing of this line should extend 0.4 Å from the center. A line as weak as this cannot have such a long wing /See Note/. This is also evident from the fact that even if we take the blue wing of the blend of the 6560.62 and 6560.570 lines which exists at 11 October 1955 and 15:00, 7 June 1955).

The last effect should be slight since the equivalent width of the depression at the center of the sun under these good conditions is not more than one fourth of the equivalent width of the 6561.105 line (Table 2, compare S_D and S_W for the center in these recordings), and its change

by 1.65 times toward the limb can cause an increase in the equivalent width of the 6561.105 line of not more than 1.16 times, which is also shown by the observational data (in Table 2 the average value is S_W (limb)/S_W (center) = 1.15).

But if the observed depression is related to D_α, then one cannot understand the slight shift of the center of this depression toward the blue as compared with the position calculated according to the isotopic shift. In fact, the mean position of 6560.89 Å for the maximum depression is determined, although with some uncertainty, with an error of not more than 0.04 Å, i.e. twice as small as the shift, which is about 0.07 Å, to the blue even with respect to the blue component of D_α at 6560.964 Å.

We have already shown in Section 1 that a depression in the H_α wing caused by the presence of D_α will be assymmetric: it would extend farther to the blue than to the red. The doublet structure would enhance this effect of assymmetry and would lead to a shift of the depression's maximum. The magnitude of this shift can be evaluated by assuming that the D_α line arises in an optically thin layer and adding the absorption coefficients for the two components of the doublet, i.e. by adding the depressions produced by the two D_α components in the H_α wing. These depressions have been calculated more rigorously by De Jager for various deuterium concentrations.

The dotted lines in Figure 9 show the depressions caused by the separate components of D_α for a deuterium concentration of $7\ 10^{-5}$ (Ref. 10), where the red and blue components are assumed to have the same intensity. The solid line shows the resulting depression caused by the two D_α components. It is known (see, for example, Ref. (19)) that for hydrogen and deuterium the H_α and D_α lines should theoretically be composed of two main components of approximately the same intensity and three very weak lines, which have practically no effect on the distribution of intensity in the two main components.

In experiments Lewis and Speding have actually observed these two main components of D_α and H_α of equal intensity, although it is generally known that their relative intensity is strongly dependent on the conditions of excitation. Since the zero-point was taken to be the wavelength 6561.088 Å of the red component of D_α and the depression's maximum is shifted by about 0.08 Å to the blue, as is evident from Figure 9, the position of the depression's maximum will be at $\lambda = 6561.088 - 0.08 = 6561.00$ Å, instead of the observed $\lambda = 6560.89 \pm 0.03$ Å. A difference of 0.1 Å cannot be ascribed to possible errors in the recording itself; its cause can only be sought in the following:

1. Inaccuracy and some arbitrariness in drawing the unperturbed contour (dotted line in Figures 6 and 7) between the 6561.105 and 6560.570 lines;

2. Insufficient resolving power, which would not define precisely the differences in contour in the region in question for the center and two limbs;

3. A possible distortion of the position of the depression from the effect of the very weak telluric line at 6560.8 (?), although, as we said above, the presence of this line could not explain the increase of the depression from the center to the limb nor the increase in the equivalent width of the 6561.105 line toward the limbs.

To remove any doubts, we made a large series of recordings on 11 November 1955, a day when there was an exceptionally low water vapor concentration, at the maximum altitude of the sun, using for this purpose another grating with a resolving power of 300,000 (in practice, the resolving power of the recordings was 0.025 Å in the third order). In Figure 10 we show typical high-resolution recordings for the center and eastern and western limbs; in Figure 11 we show the results of processing these recordings: on the right are the individual measurements (9 recordings for the eastern limb, 8 for the western limb, and 4 for the center), on the left are the average contours. Recordings were made in both directions (approximately equally) according to the scheme: two recordings for one limb, one for the center, two for the other limb, etc. For simplicity, Figure 11 shows only the sector at 6561.105 Å and the adjacent region of the depression.

Even without looking at the average contours shown on the left-hand side of Figure 11, one is struck by the difference of the distribution of individual points for the western and eastern limbs. This is particularly evident in the average contours of the 6561.105 line of water vapor: for the western limb this line has a flatter and longer red wing, while for the eastern limb the blue wing is flatter and longer (the effect of assymmetry is more than two times greater than the mean deviation from the average, which is 0.4 and 0.3% for the western and eastern limbs, respectively). For the center we have an intermediate situation. This assymmetry is clearly noticeable upon examination of the recordings: at the western limb the 6561.105 line has a flatter and longer red wing, while at the eastern limb the reverse is true. This effect is clearly visible in the recordings from 7 and 10 June 1955 (the western limb, see Figure 6) and from 11 October 1955 (see Figure 7). Further, from Figure 11 it is evident that the construction of the "unperturbed" contour in the region of the depression between the 6561.105 and 6560.570 lines may be very indefinite and possible, perhaps, only for the center.

If we now determine the equivalent width of the 6561.105 line, limiting it from the blue side $\Delta\lambda = -0.18$ Å from the center, we obtain the following values:

	S_W, mÅ	$\frac{S_W \text{ (limb)}}{S_W \text{ (center)}}$
Center	4.1	1.0
Limb, W	6.4	1.55
Limb, E	4.3	1.05

As is evident, the equivalent width of the 6561.105 line increases by at least 1.5 times toward the western limb and slightly toward the eastern limb. Further, the position of this line can obviously be considered constant from the center to the limb (it is selected as the zero-point for reckoning). At the western limb the distance to the unknown solar line at 6560.62 Å is the least (this line is shifted to the red, toward the zero-point), its blending effect is therefore greatest, and thus the depression in the sector from $\Delta\lambda$ = -0.12 to -0.30 Å is greatest at the western limb. But by virtue of this, it would be natural to expect that the 6561.105 line would have the flattest and longest blue wing at this limb. Observations indicate the opposite: the blue wing is flattest and longest at the eastern limb where the effect of blending with the 6560.62 line is least (it is generally negligible here). Therefore, the effect of the change in the assymmetry of the 6561.62 line. Neither can the increase in the equivalent width of the 6561.105 line from the center to the western limb be entirely ascribed to this effect: even if the blue wing of this line is constructed as shown by the dotted line in Figure 11, we shall still have an increase of 1.4 times in the equivalent width, an effect that cannot be considered accidental. All this indicates that the 6561.105 line is really blended with a solar D_α line [See Note]. (Note: To remove any doubts related to an imaginable possibility that the assymmetry of the contour from the center to the limb is due to the equipment, we constructed contours of the lines of atmospheric oxygen for the center and limb. No assymmetry was detected at the limb.)

Figure 11 also shows the theoretical contours of a depression caused by D_α, according to Figure 9, for an arbitrarily selected deuterium concentration of $7\ 10^{-5}$, with consideration of the shift at the limbs caused by the sun's rotation (the position of the two D_α components, as determined by the isotopic shift, are also included for all three cases). We see that the change in assymmetry and equivalent width of the 6561.105 line from the western to the eastern limb is completely in accord with the shift and change in blending effect of the D_α line. At the western limb the D_α depression is almost completely blended with the 6561.105 line, and therefore the equivalent width of this line is at a maximum and its red wing is extended because of the D_α line. Conversely, at the eastern limb the D_α depression is shifted the most toward the blue, and therefore the equivalent width of the 6561.105 line is noticeably less and the blue wing of this line is extended. If, further, we examine the red wing of the 6561.105 line, which we know is not blended with the red wing of the 6560.62 line, and subtract from its residual intensities the theoretical magnitude of the depression for the western and eastern limbs, we obtain the red wing of the water vapor lines which are free from the effect of D_α. In fact, for the assumed ratio $D/H = 7\ 10^{-5}$ we obtain magnitudes for the two limbs which coincide within the accuracy of the mean deviation.

However, if we compare the observed depth of the depression between the 6561.105 and 6560.570 lines for the western limb (when this depression is most free from blending with the solar line at 6560.62 Å) with the

theoretical depth for D/H = $7 \cdot 10^{-5}$, we are forced to conclude that this depth is at least one and a half to two times less, i.e. that D/H $\lesssim$ 3 to $5 \cdot 10^{-5}$. But with such a ratio D/H we find a divergence somewhat greater than the mean error between the red wings of the 6561.105 line for the western and eastern limbs after subtracting the proper theoretical depression from them. However, this divergence cannot be considered serious since these comparisons are for a depression calculated for the center of the disk without consideration of broadening at the limb.

The same values of D/H result from a comparison of the data of Table 2 with the equivalent widths of the theoretical depression, which, according to Ref. (10), are as follows:

D/H X 10^5	S_D (m Å)
3.5	0.7
7.0	2.2
14.0	5.5

Here the values of S_D are not corrected for the doublet fine structure; corrected values are approximately one and a half times greater. Taking, according to Table 2, S_D = 1.3 m Å for the center of the disk, we find that D/H $\gtrsim 3.5 \cdot 10^{-5}$, since the magnitude of S_D in Table 2 is only the portion of the depression related to D_α. We cannot use the values of S_D for the western limb since they may be affected by blending with the wing of the 6560.62 line. On the other hand, from the 11 October 1955 recording of the eastern limb we have S_D = 1.4 m Å, whence we find D/H $\gtrsim$ $4 \cdot 10^{-5}$.

Thus, the observations lead to a probable value of D/H $\approx$ 4 to $5 \cdot 10^{-5}$.

As far as the D_β, D_γ, D_δ, etc., lines are concerned, they are so strongly blended that their emission is practically impossible; in addition, they are much weaker than the D_α line. The D_γ (4339.287 Å) falls in the strong blend of three lines: 4339.135 (intensity 0), 4339.258 (Fe, intensity 0), and 4339.458 (Cr, intensity 4). The D_δ line falls in the strong blend of the Fe lines at 4100.167, 4100.350, 4100.749 with intensities of 2, 0, and 4, respectively. An attempt could be made only for the D_β line (4860.029 Å). In the D_β region the Rowland atlas shows the lines

4859.137	Fe	0	4860.024	(?)	-3
4859.488		-3	4860.222	Cr^+	-1
4859.749	Fe	4	4860.994	Fe	0
			4861.344	H_β	30

The Minnaert atlas and our photoelectric recordings of this region (Figure 12) show that the line in which we are interested lies in the red wing of the very strong line of Fe at 4859.749 Å. Therefore, it would

be very difficult to study it by means of the center-limb effect or to construct its profile with any certainty. Our attempts to process the photoelectric recordings gave no reliable results since it is impossible to construct the red wing of the Fe line at 4859.137 Å free from blending (the blue wing of this line is also blended with the red wing of the Fe line at 4859.137 Å).

The identification of the very weak line (intensity -3) at 4860.024 Å, as Menzel (1) suspected, with D_β becomes more reasonable if we consider the fine structure constant, which is 0.08 Å for D_β. Since the wavelength of 4860.029 Å for D_β relates to the center of a doublet, one of the components (the blue) will have a wavelength of 4860.024 Å, which exactly coincides with the wavelength of 4860.024 Å, for the unidentified line. On the whole, however, the contour of H_β is somewhat assymmetric with the greatest depression falling in the region close to D_β (Ref. 11); however, this undoubtedly could be related to the effect of the blend of the Fe and Cr + lines.

Further evidence that there are D_α and D_β lines in the solar spectrum is given by the fact that in the regions 6560.5 -- 6561.0 and 4860.0 -- 4860.2 there are no known lines of other elements, as a detailed check of contemporary tables of spectral lines (Refs. 18, 20) has shown. Also, judging by the data of Pierce and Gaydon (21), there are no molecular lines or bands in these regions.

4. Possibility of Observing Deuterium Lines in a Flare Spectrum

The intensity of an H_α line in a column passing through the chromosphere along a tangent is where k_0 is the absorption coefficient for the center of the line, $E_{32}(0)$ is emmission at the center of H_α (free from self-absorption; see, for example, Ref. (6)). The quantity

$$k_0 \approx 7.0 \cdot 10^{-13}\,\Theta^{1/2},\quad \Theta = 5040/T. \tag{4.2}$$

$N_2 k_0 = x$, then (4.1 will be

$$I_{32}(0) = \lambda\, E_{32}(0),\ \lambda = \frac{1-e^{-x}}{x} \tag{4.3}$$

For $I_{32}(0)$ the observations give a value of the order of $1.5 \cdot 10^{13}$ erg/sec cm^2 cm.

If we take the data of Menzel and Cillie (22) for initial data, then, assuming, as these authors do, that $N_2 = 10^{14}$, we obtain for a temperature $T = 5000°$ ($k_0 \approx 7.0 \cdot 10^{-13}$)

$$N_2 k_0 \approx 70,\ \lambda(H_\alpha) \approx \frac{1}{70}.$$

The quantity

$$E_{32}(H_\alpha) = 1.5 \cdot 10^{13} \cdot 70 \approx 10^{15},$$

while the intensity of emission of D_α is

$$I_{32}(D_\alpha) \approx \frac{D}{H} E_{32}(H_\alpha) \approx 5 \cdot 10^{10},$$

since self-absorption for D_α

$$x(D_\alpha) = 5 \cdot 10^{-4} \cdot \sqrt{2} \cdot 70 = 4.9 \cdot 10^{-2}$$

is negligible ($\lambda = 1$). The ratio

$$\frac{I(D_\alpha)}{I(H_\alpha)} = \frac{5 \cdot 10^{10}}{1.5 \cdot 10^{13}} = 3.3 \cdot 10^{-3}, \text{ i.e. } 0.3\%.$$

(Transl. editor's note: no omission at this point. Translator had in error repeated some lines of text).

To detect a D_α line corresponding to 0.3% of the intensity of the center of H_α, is very difficult even though the intensity of the wing of the H_α line in the D_α region is not less than several percent. Let us calculate the intensity of H_α in the chromosphere at a distance of $\Delta\lambda = 1.8$ Å, disregarding here the self-absorption [See Note], according to the formula

$$I_\lambda = \frac{N_3 A_{32} h \gamma_{32} \lambda_0}{16\pi^3 (\lambda - \lambda_0)^2}.$$

Assuming that $\gamma_{32} = 5.66 \cdot 10^8$, $A_{32} = 4.39 \cdot 10^7$, and $N_3 \approx 1.3 \cdot 10^{13}$ (in accordance with the data of Menzel and Cillie, we take the minimum value of N_3 in a column passing through the chromosphere along a tangent), we obtain

$$I(1.8\text{ Å}) \approx 10^{12},$$

)), $\lambda \equiv \frac{1 - e^{-x}}{x}$.

not less than 6% of the intensity at the center of H_α, i.e. D_α ot more than 5% of the intensity of the background (the H_α wing), which is not easy to detect by the photoelectric method. (Note: The absorption coefficient $k\lambda$ at 1.8 Å from the center is $2.24 \cdot 10^{-5} k_0$ (Ref. 13), and therefore $N_2 k_0 \approx 1.7 \cdot 10^{-3}$ and $\lambda \approx 1$, i.e. self-absorption is negligible)

If we consider that in Mitchell's catalog (23) of the spectral lines in a flare the weakest line near H_α, Ti^+ at 6559.59 Å (twice as far as D_α), has an intensity of about 0.5%, then D_α is somewhat below the detection limit in Mitchell's eclipse spectrograms. If $D/H \approx 3 \cdot 10^{-5}$, then it is almost as probable as $5 \cdot 10^{-5}$ that the contrast of D_α as compared to H_α will be still less (about 0.1%) and the D_α line will be very difficult to detect even on good spectrograms of a flare (especially if we consider that atmospheric roughness washes out the image of the chromosphere).

It is even more difficult to detect D_α without an eclipse: if the brightness of the halo is $\sim 10^{-2} I_\odot$, and the brightness of the center of H_α is not more than $0.1 I_\odot$, then $I(D_\alpha) \approx 3 \cdot 10^{-3} \cdot 10^{-1} I_\odot \approx 3 \cdot 10^{-4} I_\odot$, i.e. not more than 3% of the brightness of the halo, which is ordinarily beyond the limits of accuracy of photography (photoelectric recording of the chromosphere is difficult because of the low brightness). We must remember that all this discussion concerns the lowest layers of the chromosphere; in higher layers the contrast $I(D_\alpha)/I(H_\alpha)$ will fall rapidly because of the decrease of self-absorption in H_α. ($I_{32} \rightarrow E_{32}$ and $I(D_\alpha) \approx (D/H) I_{32}$ for the upper layers). Approximately the same situation will obtain for the other D lines in a flare spectrum, with the sole exception that blending with neighboring lines is even greater). Therefore, to detect deuterium lines in a flare spectrum for a concentration $D/H \lesssim 5 \cdot 10^{-5}$ is a very difficult task and is hardly solvable with the present methodology for obtaining this spectrum.

5. The Possibility of Thermonuclear Exhaustion of Deuterium and Lithium on the Sun

The chief result of our study, that the deuterium concentration in the solar atmosphere is between 3 and $5 \cdot 10^{-5}$ of that of hydrogen, indicates either a greater exhaustion of deuterium on the sun or a greater exhaustion of hydrogen on the earth in the course of their joint evolution over a period of about 10^9 years (deuterium concentration on the earth is $1.5 \cdot 10^{-4}$).

Dissipation of deuterium and its compounds (DH) on the earth proceeds more slowly than does the dissipation of hydrogen, which could have led to greater (as compared with the sun) exhaustion of hydrogen and a greater relative deuterium concentration on the earth. However it is difficult to reconcile this explanation with the difference (by a factor of 100) between the relative concentrations of lithium on the earth and sun (Ref. 2). Also the effectiveness of thermal dissipation during the earth's evolution is not clear. Therefore, the differences in concentrations for lithium, beryllium, and deuterium are ascribed to a process of "burning up" of these [illegible]n thermonuclear reactions in the sun. In fact, if at the be- [illegible] the simultaneous evolution of the sun and earth their deuterium [illegible]ions were the same, say N(0), then after a time of evolution of the order of 10^9 years, as a result of the thermonuclear reactions $D + H \rightarrow He^3 + \gamma$, the deuterium concentration will change and will be defined by

$$N(t)/N(0) = e^{-10^9/\lambda_D(T)}, \tag{5.1}$$

where $\lambda_D(T)$ is the mean lifetime of deuterium at temperature T. For $T \approx 10^7$ deg, $\lambda_D(T)$ is of the order of 6 sec, and deuterium should be almost completely absent. If the mixing of matter within the sun were complete, we would not detect any traces of deuterium in the sun's atmosphere. The same argument is valid for lithium. Inasmuch as there is lithium in the

0), $\lambda \equiv \frac{1-e^{-x}}{x}$.

sun's atmosphere, Greenstein (2) was the first to conclude that mixing inside the sun is incomplete and encompasses only the outer shell, where the temperature does not exceed a value T_L which is defined by

$$e^{-10^9/\lambda_L(T)} = 0.01, \qquad 0.01 \tag{5.2}$$

i.e. mixing occurs only to the depth at which thermonuclear reactions with the participation of lithium provide its observed concentration with respect to its initial concentration, which coincides with that on the earth (the function $\lambda(T)$ falls rapidly with increase in T). Calculation of T_L from formula (5.2) gives a value of $3.1\ 10^6$ deg, which corresponds to a distance from the center of the sun of about one half of its radius.

If the same arguement is applied to deuterium, as did, for example, Crespin (9) for a deuterium concentration of about 10^{-2} of that on the earth (according to Menzel's data), then the temperature at the lower boundary of the region in which mixing should occur is found to be $6.5 \cdot 10^5$ deg. If we assume for deuterium, according to our data, a value of $N(t)/N(0)$ from 1/3 to 1/5, then from (5.1), $\lambda_D(T) = 0.6$ to $0.9 \cdot 10^9$ years, and, according to Fowler's data (24), a magnitude of $T_D \approx 5.6 \cdot 10^5$ deg, which corresponds to a distance from the center of the sun of about 0.8 of its radius. Thus, the data on the concentrations of lithium and deuterium give differing (by a factor of 7 for temperature and 3 for depth) thicknesses of the outer shell of the sun in which mixing should occur. If we assume that mixing occurs in the shell determined according to the lithium concentration ($T \leq T_L$), then there would be no trace of deuterium in the solar atmosphere since for $T_L = 3.1 \cdot 10^6$, $\lambda_D \approx 0.05$ years and $N(t)/N(0) = e^{-10^9/0.05}$. This will also be valid for a deuterium concentration of 10^{-6}. If, on the other hand, we assume that mixing occurs only in the shell determined according to the deuterium concentration ($T \leq T_D \leq T_L$), the lithium concentration on the sun will practically coincide with that on the earth. Hence, it is often concluded (e.g. in Ref. 9) artificially and incorrectly that the depth of the mixing zone changed during the course of

0), $\lambda \equiv \frac{1-e^{-x}}{x}$.

This result actually indicates that if deuterium and lithium are present in the solar atmosphere (and there are all the grounds for this), neither the concept of complete mixing nor that of partial mixing (Greenstein) can be maintained. If we do not consider the little-founded possibility that there was a serious initial difference in the chemical compositions of the sun and earth (all the previous discussions are based on the assumption of the identical initial chemical compositions), the difference between the relative concentrations of deuterium and lithium on the sun and on the earth cannot be ascribed to the effect of thermonuclear reactions. Moreover, the existence of rather intense convection and of such heavy elements as thorium and gold at the sun's surface is evidence of even complete mixing.

If, nevertheless, the hypothesis of thermonuclear reactions as the chief source of solar energy is maintained (and there is at present no pressing need to relinquish this hypothesis), we must conclude that nuclear processes (possibly nuclear disintegration, fission, or nuclear explosions) in which elements such as lithium and deuterium are formed occur in the outermost layers of the sun. The author came to this conclusion as early as 1953 (Ref. 24) from a study of the development and special character of emission of chromospheric flares. Further studies of the emission from flares and corpuscular ejections from faculae have confirmed this point of view (Ref. 25). Special articles will be devoted to this question.

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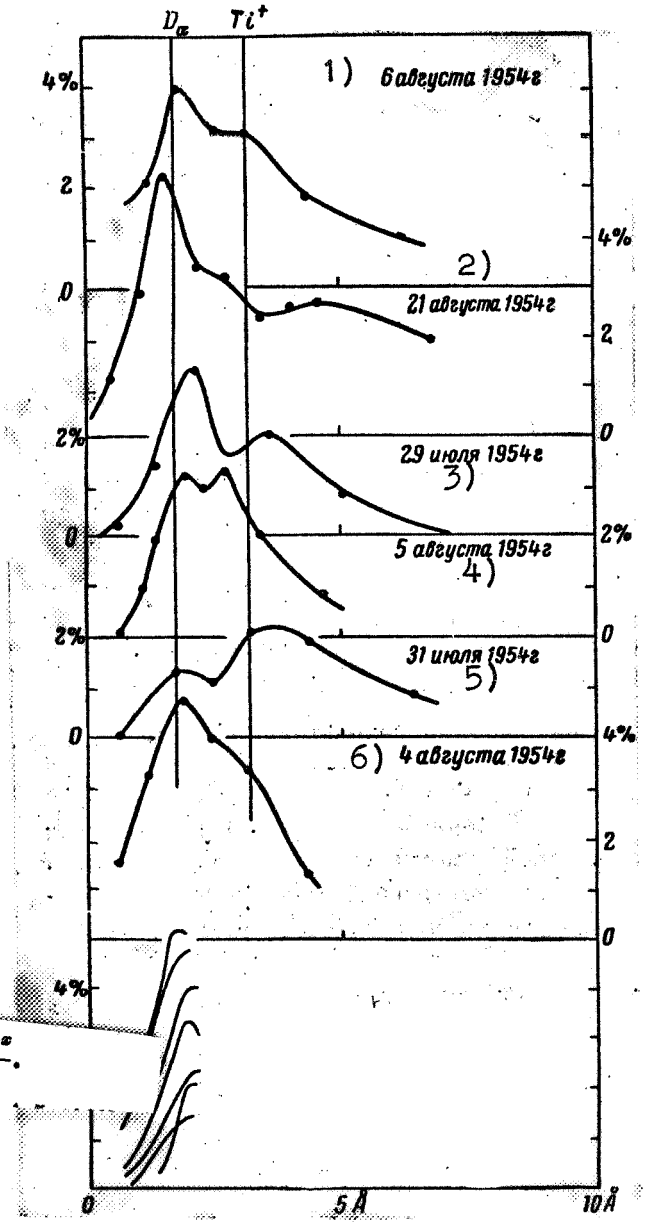
$\lambda \equiv \frac{1-e^{-x}}{x}$.

FIGURE APPENDIX



1) 6 August 1954

2) 21 August 1954

3) 29 July 1954

4) 5 August 1954

5) 31 July 1954

6) 4 August 1954

Figure 1. Depression in the blue wing of H_α in individual recordings of 1954.

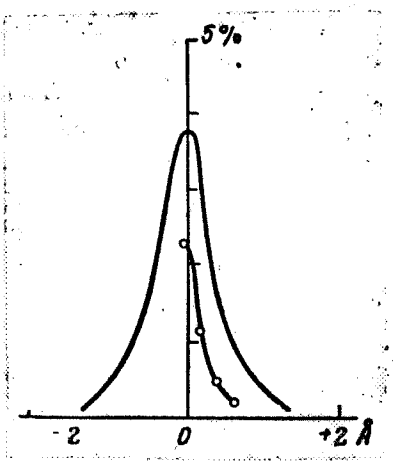


Figure 2. Mean contour of the depression and the theoretical contour (open circles).

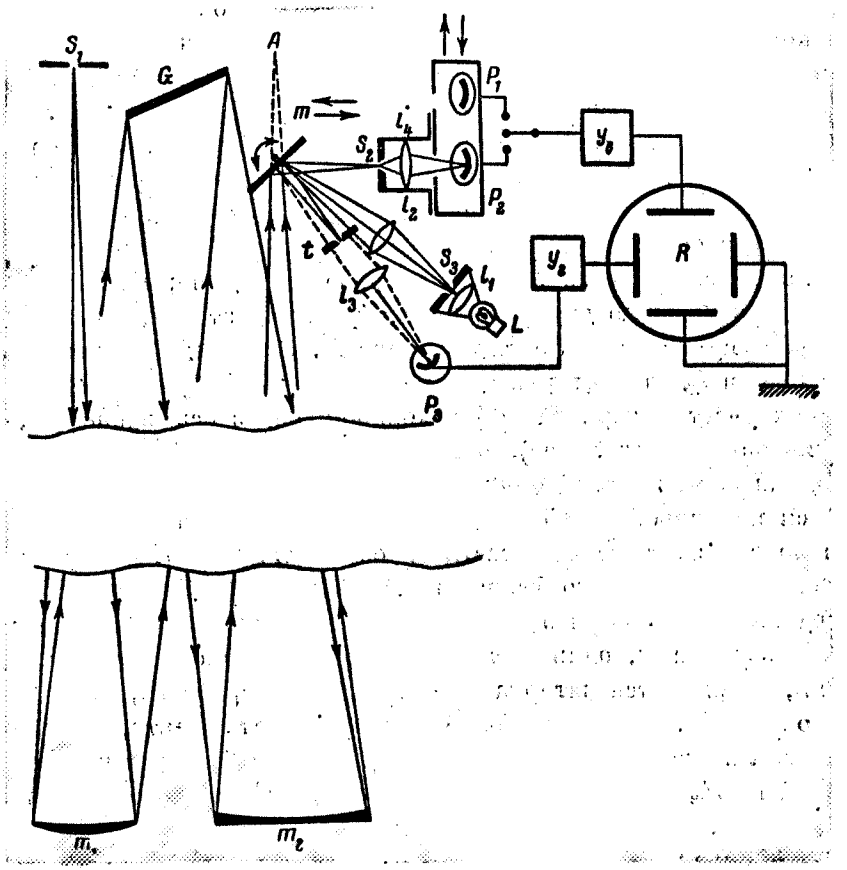


Figure 3. Diagram of equipment for photoelectric recording of solar spectra on BST.

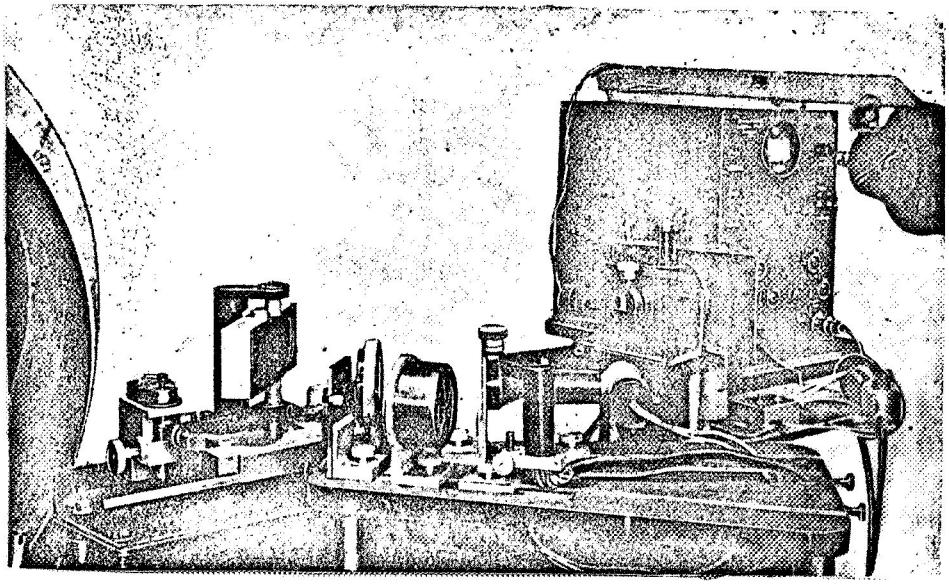


Figure 4. Overall view of photoelectric device.

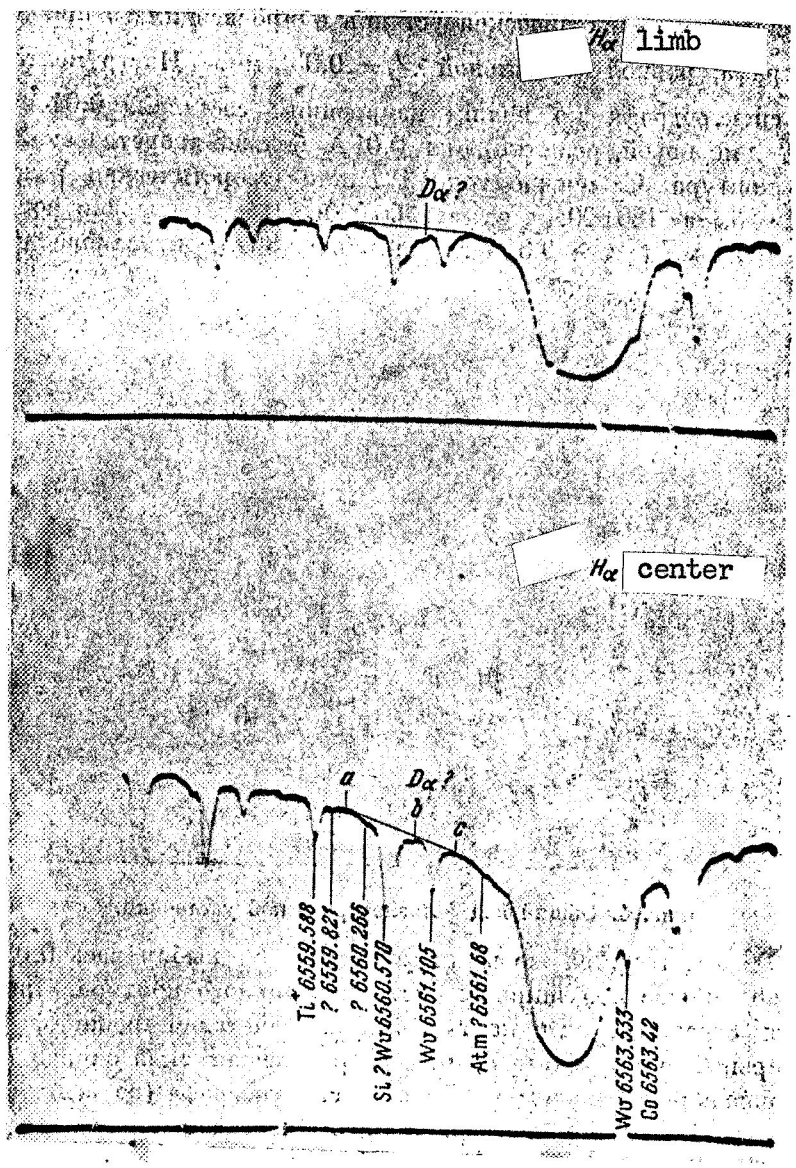


Figure 5. Example of photoelectric recording of the blue wing of H_α at the center and limb of the disk.

$\lambda \equiv \frac{1-e^{-x}}{x}$.

1) center

2) limb 3) 7 June 1955, 0715 hrs etc

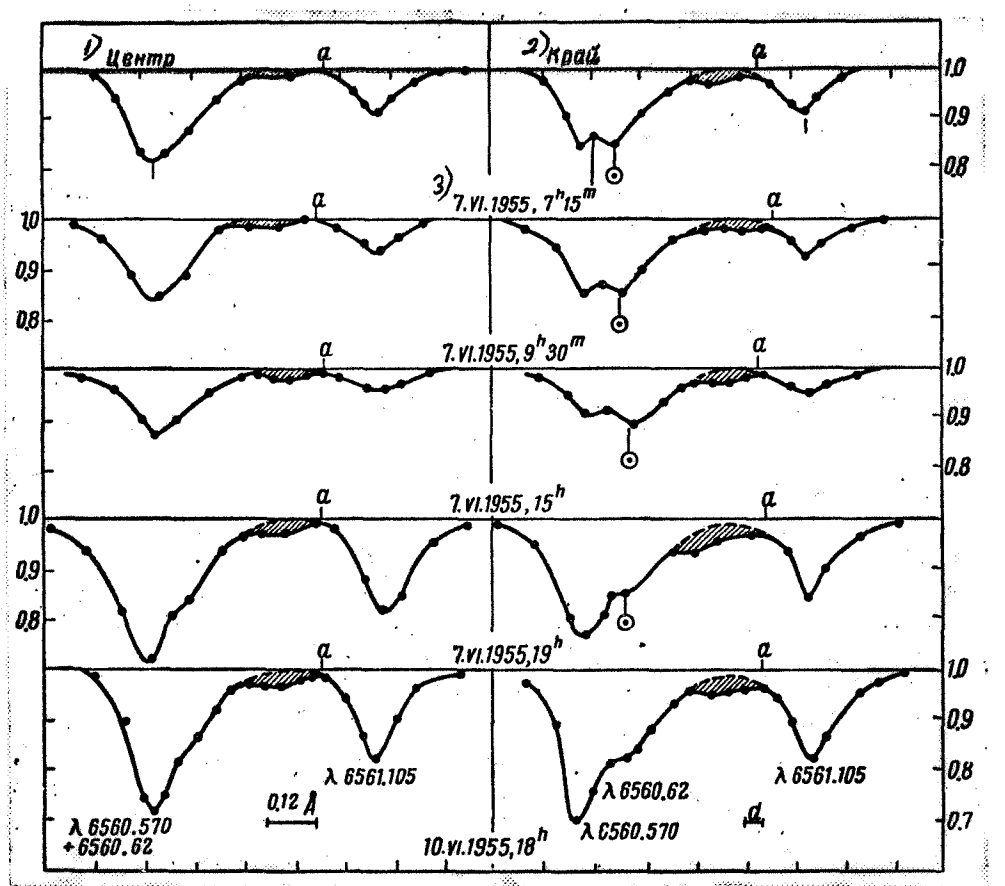


Figure 6. Mean contours of sector 6561.105 - 6560.570 Å at the center and limb.

0), $\lambda \equiv \frac{1-e^{-x}}{x}$.

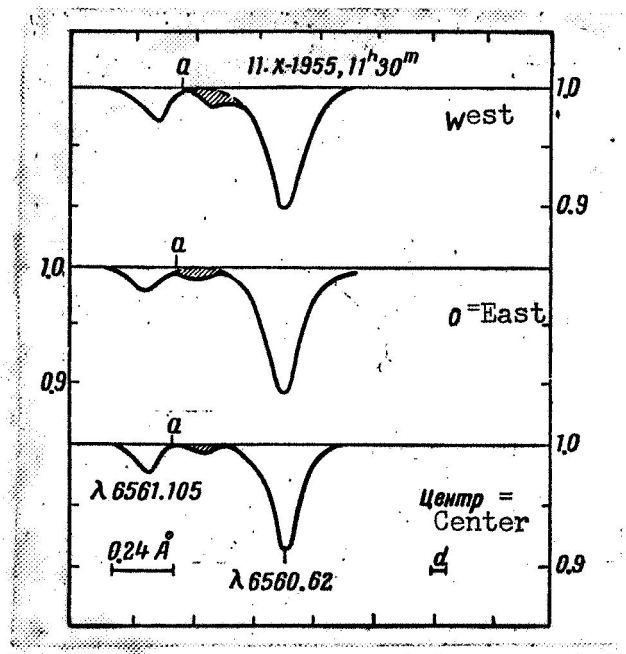


Figure 7. Mean contours of sector 6561.105 - 6560.570 Å at the center and limb from recordings at 11:30 on 11 October 1955.

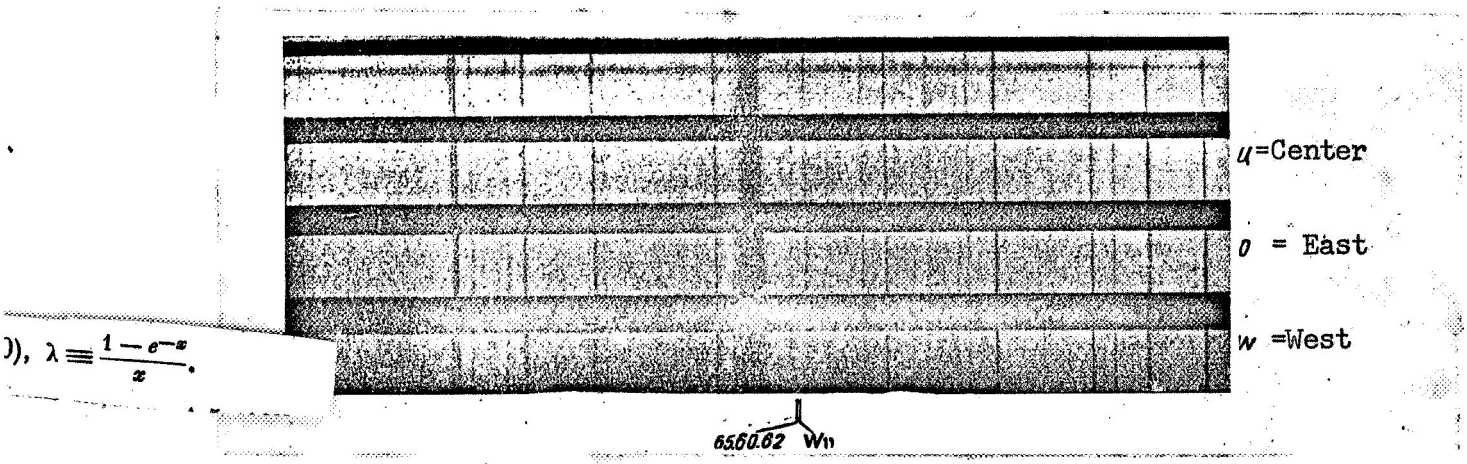


Figure 8. Photograph of H_α region of solar spectrum at the center and limbs. At the western limb the 6560.570 line separates into two lines.

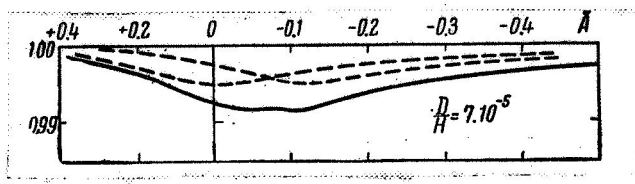


Figure 9. Theoretical contours of the depression from separate components of D_α (dotted line) and of the resulting depression (solid line).

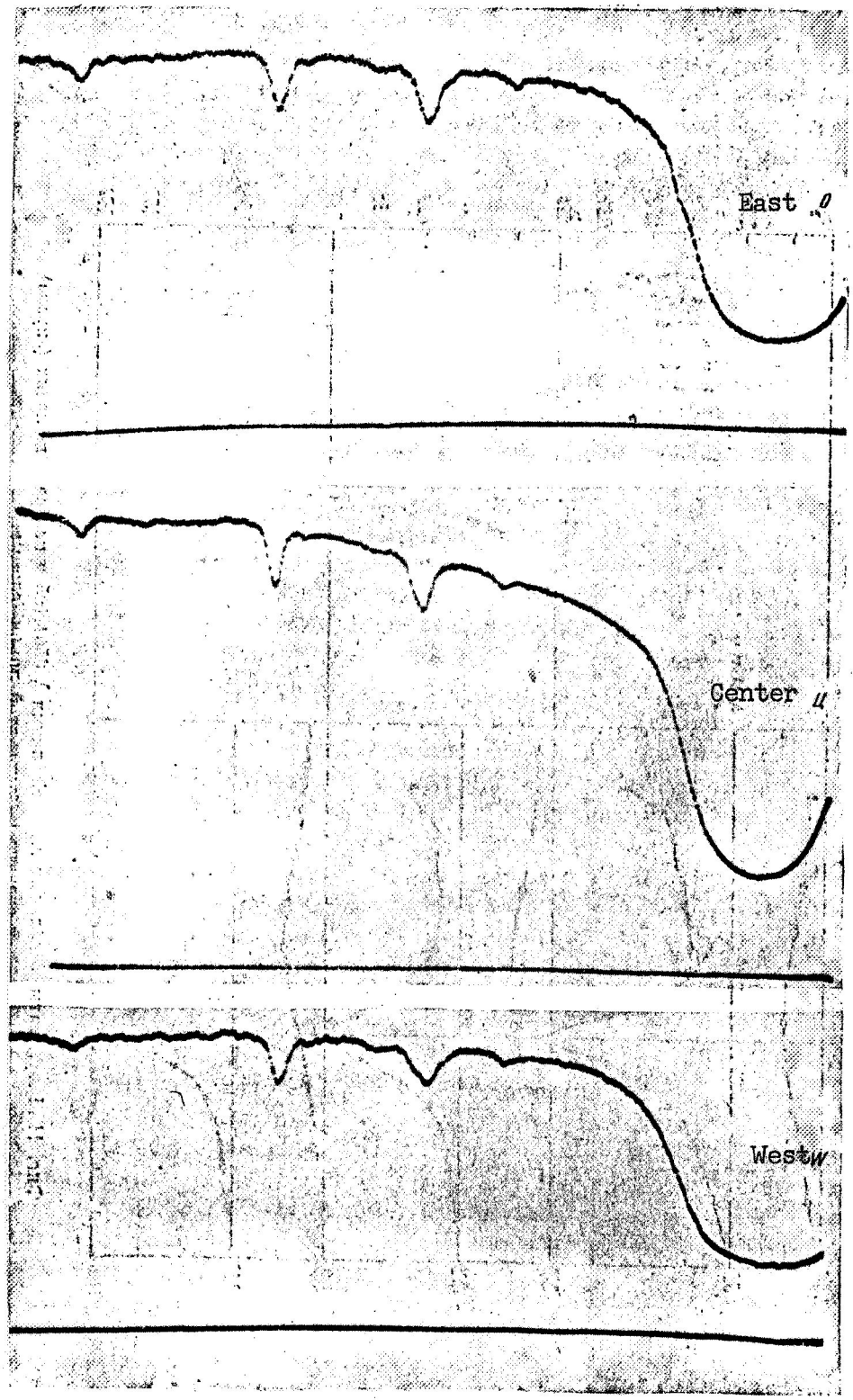


Figure 10. Examples of photoelectric recordings of the blue wing of H_α at the center and limbs under high resolving power.

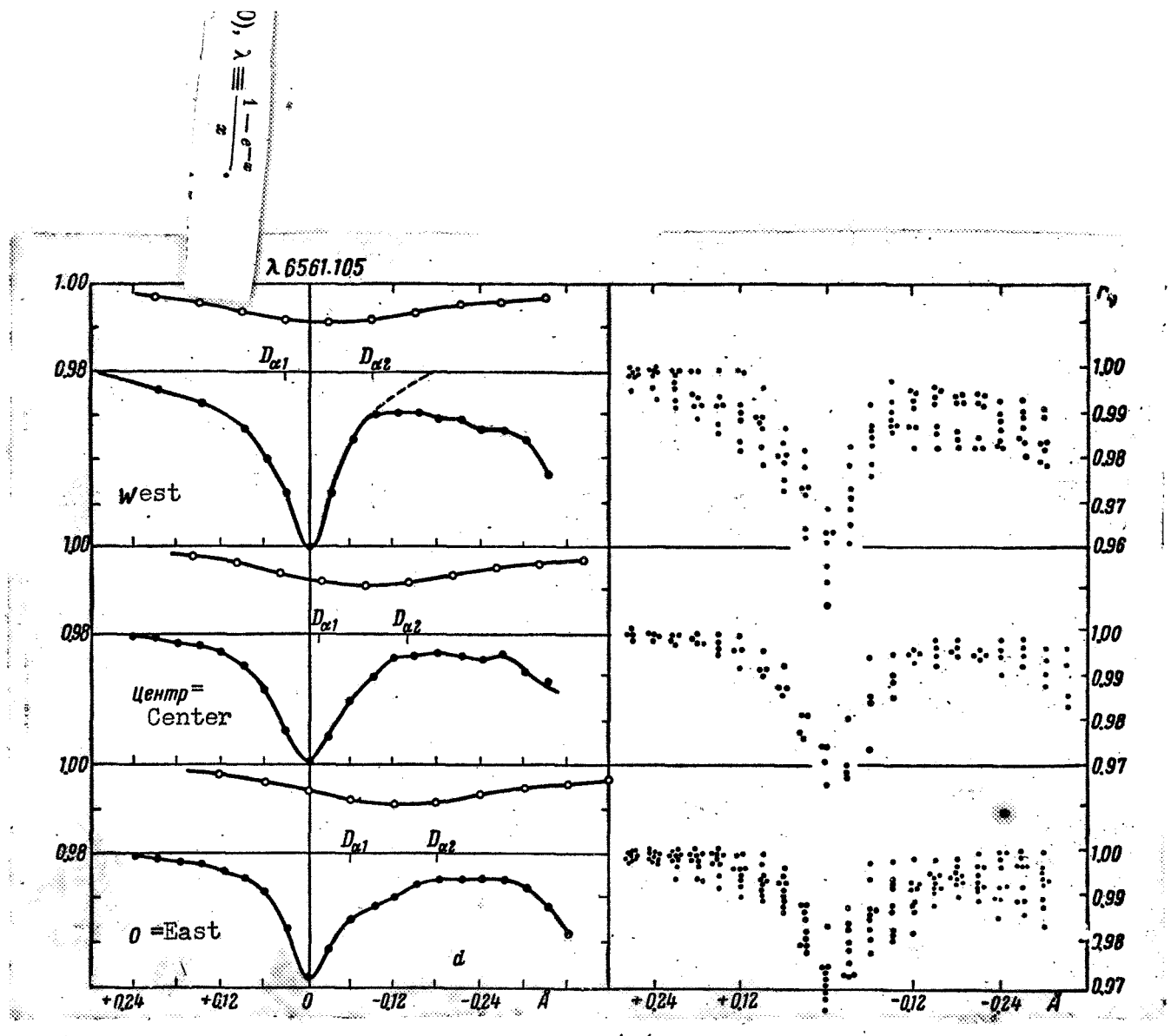


Figure 11. Results of individual recordings of the 6561.105 line at the center and limbs (on the right and the mean contours of this line (on the left); open circles show the theoretical contour of a depression caused by Dα for a concentration of D/H = $7 \cdot 10^{-5}$.

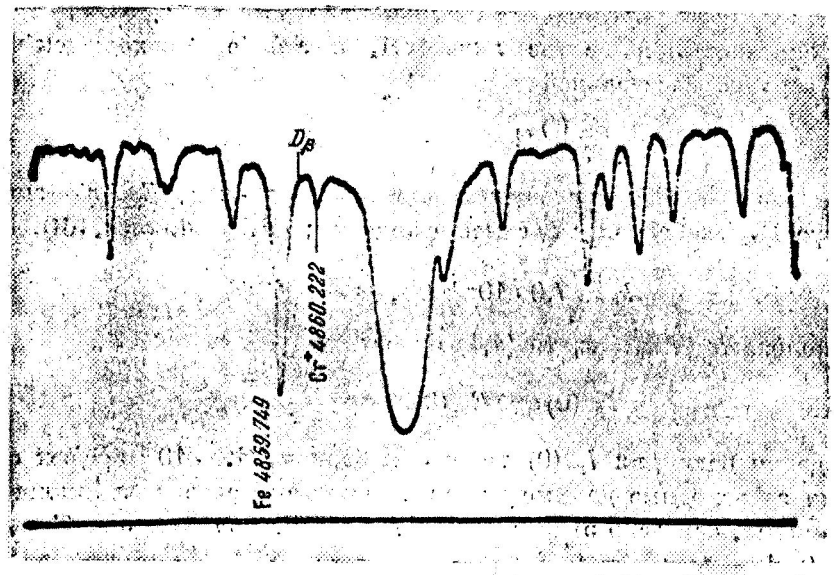


Figure 12. Example of photoelectric recording of the H_β region of the solar spectrum.

(0), $\lambda \equiv \frac{1-e^{-x}}{x}$.

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(0), $\lambda \equiv \frac{1-e^{-x}}{x}$.